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A LARGE VEHICLE PORTAL MONITOR FOR PERIMETER SAFEGUARDS APPLICATIONS

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Abstract

We have developed a class of vehicle portal monitors based on shielded 4π geometry neutron counting. We have derived and experimentally verified an analytical expression relating the detection sensitivity of the "neutron tunnel" vehicle portal monitor to four design parameters of the system. For a given number of neutron detectors, this design achieves one or more orders of magnitude improvement in nuclear materials detection sensitivity over previous vehicle portal monitors.

1. Introduction

Maintaining an effectively safeguarded perimeter around nuclear fuel storage and processing facilities is of increasing concern. In particular, vehicular traffic in and out of such facilities presents major surveillance problems. Hand-held instruments used in a manual search mode are not, generally, a satisfactory solution to this problem.

We propose using a nonintrusive, shielded, vehicle portal monitor based on neutron detection in a 4π solid angle counting geometry. This monitor is a shielded polyethylene-lined structure large enough to accomodate the largest vehicle requiring inspection. On the enclosure walls and ceiling, we place a grid of ^{3}He filled proportional counters to provide neutron detection. A vehicle is counted when it is driven into the enclosure. Comparison with the expected no-materials background determines the presence or absence of nuclear material within the vehicle. A picture of our prototype "neutron tunnel" vehicle portal monitor is shown in Fig. 1.

2. Neutron Physics of the Detection System

In a slab-geometry neutron detection system, detection efficiency is proportional to detector solid angle with typical maximum observed intrinsic detection efficiencies of better than 5-10% for fission spectrum neutrons. Because of the simple proportionality to solid angle, such systems also display a highly nonuniform sensitivity for nuclear material placed at different locations within and along a vehicle. With typical passenger and light truck vehicles, the sensitivity can range over a factor of 5-10. Usually, the vehicle inspection station at a nuclear materials facility is located in a high and/or variable neutron background environment. This generates a correspondingly high and/or fluctuating background in slab detectors with attendant loss of nuclear materials detection sensitivity.

In our shielded 4π neutron detection system, on the other hand, we observe a greatly enhanced detection sensitivity. The multiple reflection of moderated neutrons within the polyethylene enclosure is responsible for this observation. Based on solid angle calculations, we observe typical intrinsic detection efficiencies in excess of 100% for fission spectrum neutron sources. If proportional counters are uniformly spaced along the enclosure walls and ceiling, as shown in Fig. 1, we observe a uniform sensitivity as a function of nuclear material position within the vehicle. Geometrically, we observe this uniformity to be $\pm$ 1% everywhere within light truck and passenger vehicles within a 2.44 m x 3.05 m cross section enclosure 6.10 m long. (These are the dimensions of the prototype neutron tunnel shown in Fig. 1). We see local perturbations in sensitivity due to neutron absorbing or moderating materials within the vehicle, but these are generally at the $<\pm$ 10% level, as shown in Fig. 2.

Because the vehicle to be inspected and the detection system are surrounded by the polyethylene enclosure, it is feasible and desirable to provide external neutron shielding around this enclosure. This eliminates high and/or fluctuating neutron backgrounds produced by nearby nuclear materials storage or handling and results in enhanced detection sensitivity for nuclear materials within the vehicle inspected.

3. Experimental and Calculational Results

We have built and tested model enclosures ranging in size from a total enclosed surface area of 2 m^2 to 82 m^2. The 82 m^2 enclosure is suitable for inspecting light trucks and passenger vehicles (Fig. 1). Monte Carlo neutron code calculations have been performed for enclosures up to 520 m^2, an appropriate size for inspecting railroad freight cars and large tractor trailer units.

With all enclosure sizes, we have found uniformity of response independent of position within the enclosure, (Fig. 2). We have also found that the efficiency of enclosures of different sizes scales simply as the ratio of projected proportional counter area to enclosure surface area. The scaling is accurate to about $\pm$ 10% over the tested range of 2 m^2 to 520 m^2. The proportionality constant in the scaling factor depends principally upon detector properties, neutron source energy, and thickness of the reflecting polyethylene layer.

For 5.08 cm diameter proportional counters filled with ^{3}He to 2 atm, a 2.54-cm-thick polyethylene reflecting layer ($\geq$ 20-cm-thick concrete walls are assumed to shield the polyethylene liner and produce additional reflection) and bare fission source neutrons, the proportionality constant is K= 1.7 ± 0.2. If the ^{3}He counter pressure is lowered to 1 atm, K = 1.2. If the polyethylene liner thickness is decreased to 1 cm (≥ 20-cm-thick concrete walls) K = 1.4. If a bare AmF source is used, K = 2.0; if a moderated (5 cm polyethylene moderator) fission source is used, K = 3.0.

4. Detection Sensitivity as a Function of Enclosure Parameters

The sea level equivalent cosmic-ray background for 5.08 cm diameter, 2 atm ^{3}He proportional counters is about 7 cps per m^2 of projected counter surface area. The largest individual counters we have used are 5.08 cm in diameter x 183 cm long, or 0.093 m^2 in projected area. This prototype tunnel shown in Fig. 1 contains 30 such proportional counters for a total projected area of 2.79 m^2. If it is assumed that the enclosure shielding provides a cosmic-ray shielding factor of S, then a proportional counter detector system of projected area $A_{pc}(m^2)$ develops an average background count of

$$B \cong \frac{7\ A_{pc} T}{S} \tag{1}$$

in a counting time of T seconds. ($S \cong 1.4$ for 25 cm of concrete and $S \cong 30$ for 5 m of dirt.)

Consider a net signal level 5σ above this background count as being an appropriate nuclear materials detection level. If M_{min} is the minimum nuclear material neutron source (in neutrons per second) giving rise to this signal, then we can equate:

$$\text{Net signal} = \frac{M_{min}\ KTA_{pc}}{A_T} = 5\sqrt{B} \tag{2}$$

where A_T is the enclosure surface area in m^2 and for a fission source (and 2 atm ^{3}He counters) K = 1.7. Combining Eq. (1) and Eq. (2) leads to:

$$M_{min} \cong \frac{7.8\ A_T}{\sqrt{STA_{pc}}} \quad . \tag{3}$$

Thus, we have a simple expression for the enclosure's detection sensitivity in terms of its design parameters: A_T (size), S (cosmic-ray shielding), T (inspection time), and A_{pc} (number of proportional counters). For the 82 m^2 prototype tunnel, with 30-5.08 cm x 183 cm proportional counters, S = 1.4 (25 cm concrete), and an inspection time of 10 s, we obtain M_{min} = 102 n/s. For an inspection time of 200 s, M_{min} = 23 n/s. The latter value corresponds to about 0.1 g of typical reactor grade plutonium oxide or about 0.6 kg of UF_6 feed material. In a 520 m^2 enclosure, the minimum detectable signal is a factor of about six greater than the above example if all other parameters are constant.

Equation (3) can be used to trade off engineering, architectural, cost, and counting-time constraints to obtain an optimal system.

In Fig. 2 we show the results of actual vehicle inspections done with nuclear materials in a typical half-ton American made pickup truck. We did the measurements in the unshielded neutron tunnel shown in Fig. 1 at an elevation of 2000 m above sea level. With the 2000 m cosmic-ray background, we observed an average reactor grade PuO_2 sensitivity for 200 s inspections (5σ above background) of 270 mg. When these data are scaled to the more typical sea level cosmic-ray background levels inside a lightly shielded (S = 1.4) tunnel, the 5σ sensitivity is 100 mg of reactor grade PuO_2.

5. Effects of Nuclear Materials Shielding on Sensitivity

Neutronics shielding around nuclear material in a vehicle decreases detection sensitivity in proportion to its shielding factor. Because neutron shielding is bulky, concealing large masses of nuclear materials from the tunnel detection system requires large shielding masses. To provide a factor of 100 reduction in fission neutron output, for example, requires a borated polyethylene shielding thickness of about 25 cm, which corresponds to 100 kg or more. Preliminary measurements with the 82 m^2 tunnel show that ≥ 20 kg of borated polyethylene or an equivalent thermal neutron absorber produces a detectable perturbation in the neutronics properties of the enclosure. The perturbation is easily observed by introducing a weak source of thermal neutrons in the vicinity of the neutron absorber. This measurement might allow detection of massively shielded neutron materials even though the shielding itself prevents a direct detection. The number of "legitimate" borated polyethylene bearing vehicles is likely to be small, making the false alarm rate from such inspections correspondingly small.

We also find that the presence of neutron absorbing materials reduces neutron tunnel cosmic-ray background. In particular, Fig. 3 shows the absorbing effects of iron and the observed change in cosmic-ray background as a function of vehicle mass.

6. Use of Inspection Data

The previously described tunnel enclosure detection system, when coupled with an appropriate microprocessor and data processing algorithm, provides an "alarm" go/no go type output with automatic background update. Quantitative results can also be easily recorded. Then, with suitable analysis, such as is discussed in a companion paper by C. N. Henry, the results of several days, weeks or even months of inspections can be analyzed collectively, greatly enhancing the probability of detection of a systematic "sub threshold" diversion of nuclear materials.

7. Conclusion

We developed a class of vehicle portal monitors based on shielded 4π geometry neutron counting. We constructed and tested various sizes of prototype portals. Discovery of a simple general scaling law enables us to determine analytically the effects of system design parameters on system sensitivity. Equation (3) gives this simple functional dependence.

Typical system sensitivity for a "tunnel" enclosure is one or more orders of magnitude greater than that obtained with the same number of proportional counters used in a conventional slab geometry. The tunnel enclosure system displays a highly uniform sensitivity for nuclear materials in any part of the vehicle and is intrinsically shielded from external backgrounds.

The ^{3}He proportional counters used in this system are highly reliable. The prototype system containing 30 proportional counters (Fig. 1) has been in continuous operation for over three months without a single malfunction of a proportional counter or of counting electronics.

Figure Captions

Fig. 1. Prototype "Neutron Tunnel" vehicle portal monitor.

Fig. 2. Nuclear materials detection sensitivity as a function of position within neutron tunnel.

Fig. 3. Effect of vehicle mass on tunnel background.

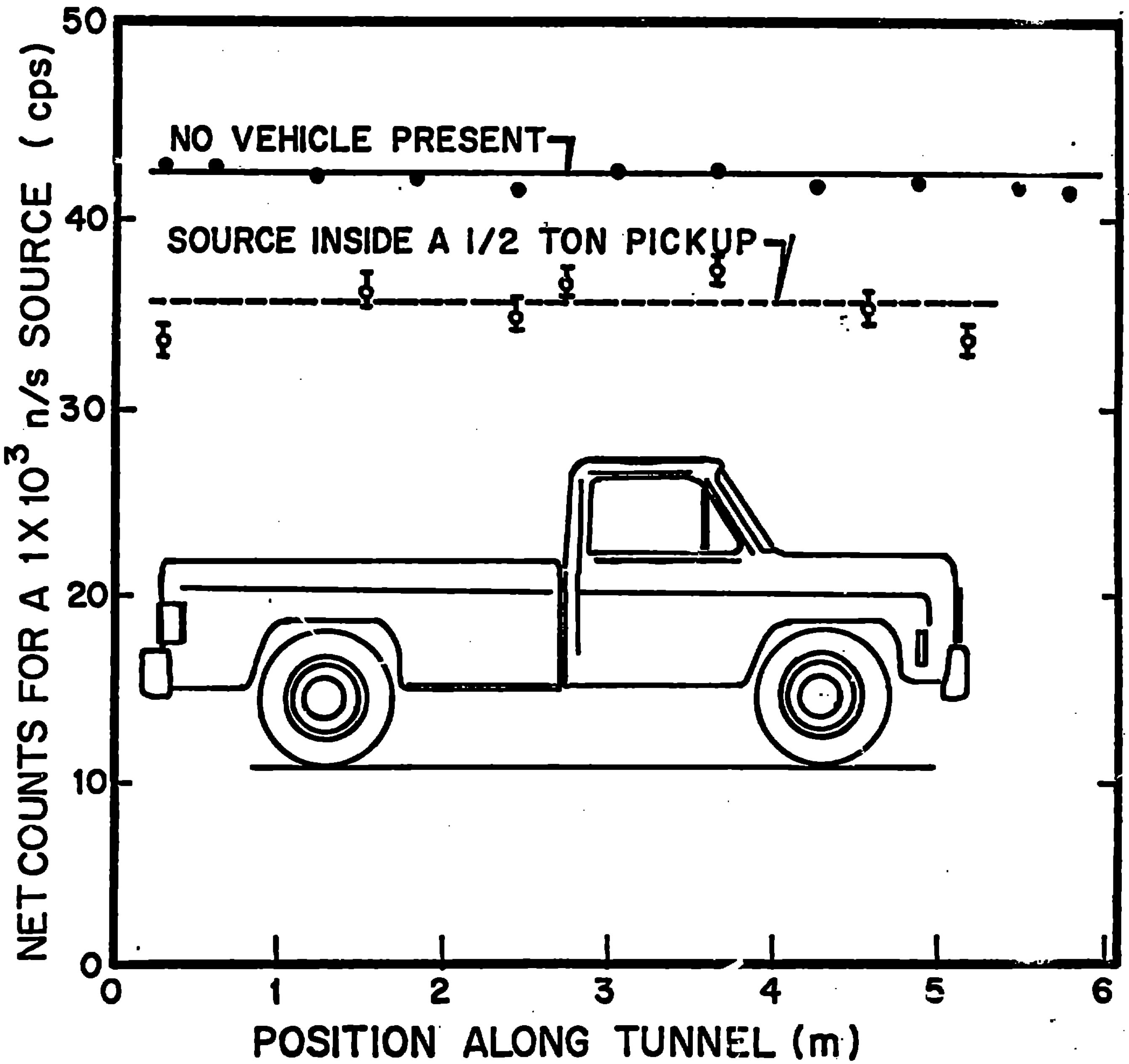
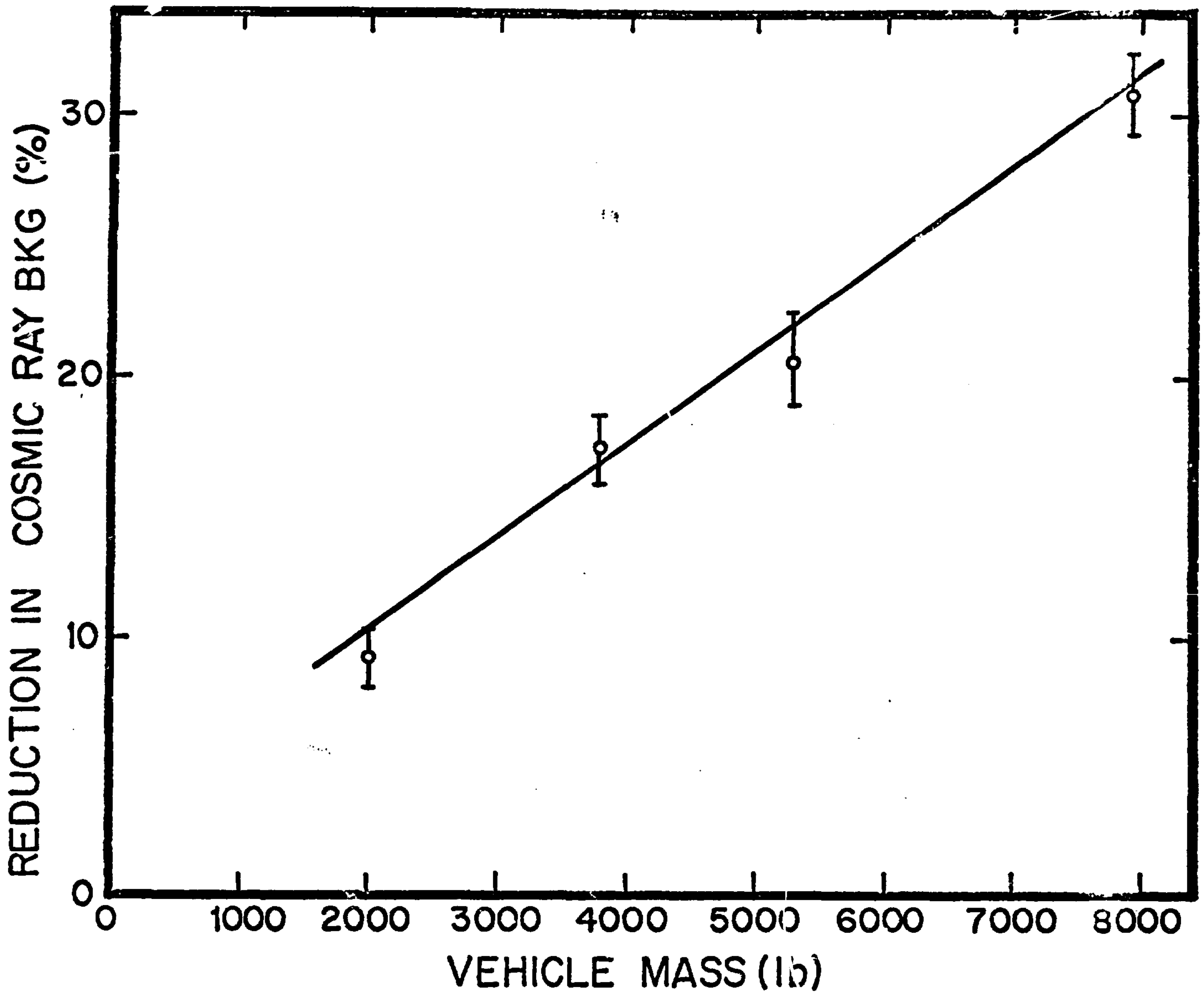


Fig. 2

Nuclear materials detection sensitivity as a function of position within neutron tunnel.



EFFECT OF VEHICLE MASS ON TUNNEL BACKGROUND

Fig. 3